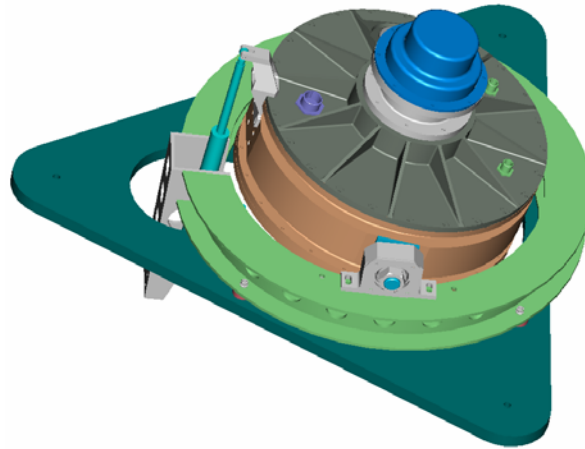


AFRL/NASA Flywheel Program Overview

14 Mar 02



Dr. Jerry L. Fausz

Program Manager

Space Vehicles Directorate

Air Force Research Laboratory



Glenn Research Center



Outline



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- ✓ **Introductory remarks**
- **Technical challenges**
- **Dual use objectives**
- **AFRL/NASA Program**
 - **System developments**
 - **Government facilities**
 - **Base R&T**
- **Concluding Remarks**



Flywheel Anatomy 101



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Flywheel:

A device that stores energy in the form of kinetic (rotating) mass and delivers electrical energy on demand.

Rotor:

high strength, long life
lightweight carbon fiber
composite;
shaft-hub-rim assembly

Magnetic Bearings:

high flux, efficient
two sets - upper/lower

Enclosure:

lightweight aluminum to
ensure vacuum; provides
spacecraft mechanical
and thermal interface

Motor/Generator:

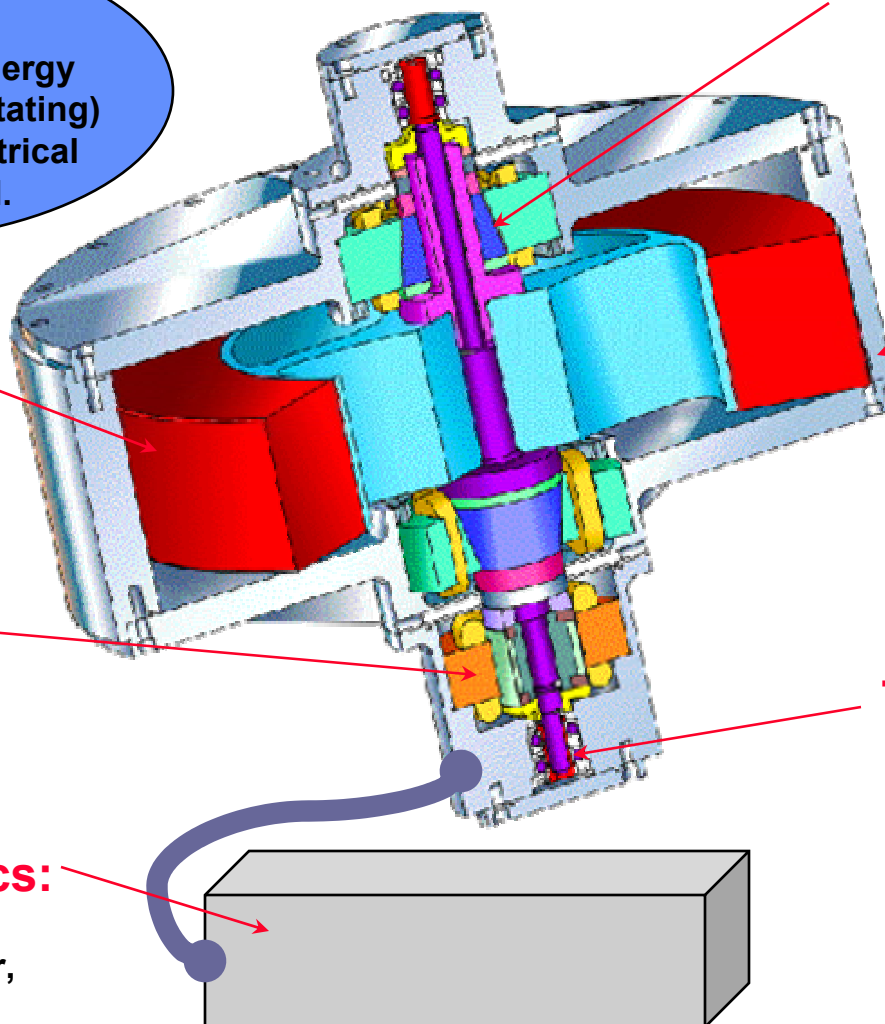
High speed, high efficiency
non-contact DC motor

Touchdown Bearings:

High speed, high impact,
mechanical ball bearings

Associated Electronics:

motor/generator drive,
magnetic bearing controller,
ACS interface

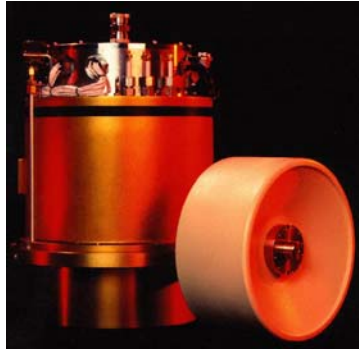




Flywheel Energy Systems



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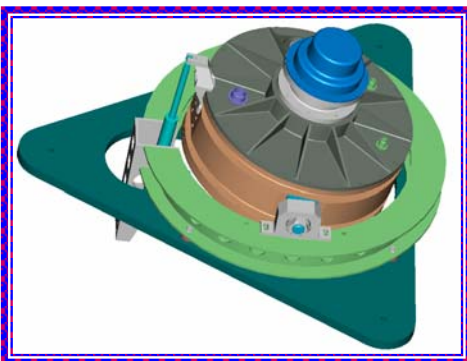


Flywheel Energy Storage (FES)

- 2 counter-rotated flywheels
- Energy storage
- Replace some Power Management & Distribution (PMAD)

Integrated Power & Attitude Control System (IPACS)

- Array of ≥ 2 FWs
- Energy storage & Attitude control torque
- Replace some PMAD



Flywheel Attitude Control, Energy Transmission & Storage (FACETS)

- System Level – Full 3-axis Attitude Control with Simultaneous Energy Storage



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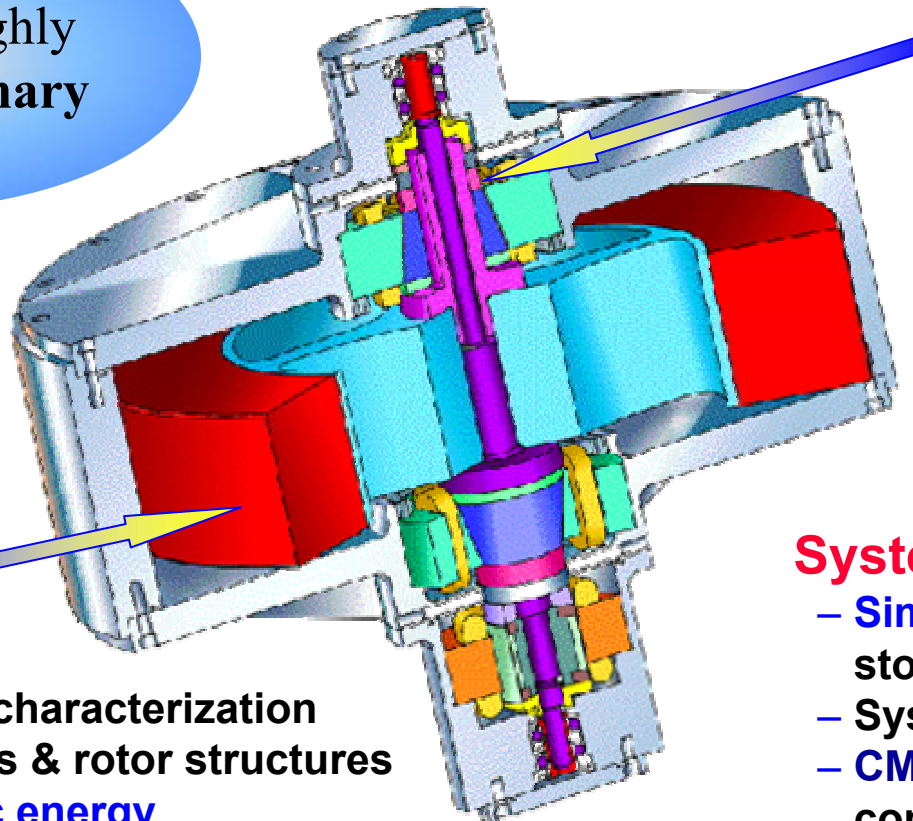


Technical Challenges



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Flywheel systems represent a highly **multi-disciplinary** challenge



Rotor:

- **SAFETY**
- Rotor Safe Life characterization
- Material systems & rotor structures for **high specific energy**
- Health monitoring/ fault recovery

Magnetic Bearings:

- **Base motion:** gimbaling
- **Disturbance rejection**
- **Reduce Losses**

System Level:

- **Simultaneous** energy storage & attitude control
- System level **efficiency**
- **CMG mode** attitude control with variable speed momentum wheels



Programmatic Challenges



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- **Development**

- Bus technology: **Low priority**
- Simultaneous AC & ES control

- **Demonstration**

- Modeling and simulation: **Simultaneous control**
- Safety

- **Transition**

- Revolutionary : **“we’ve never flown one before”**
- Pervasive: **Challenge to user confidence**



Outline



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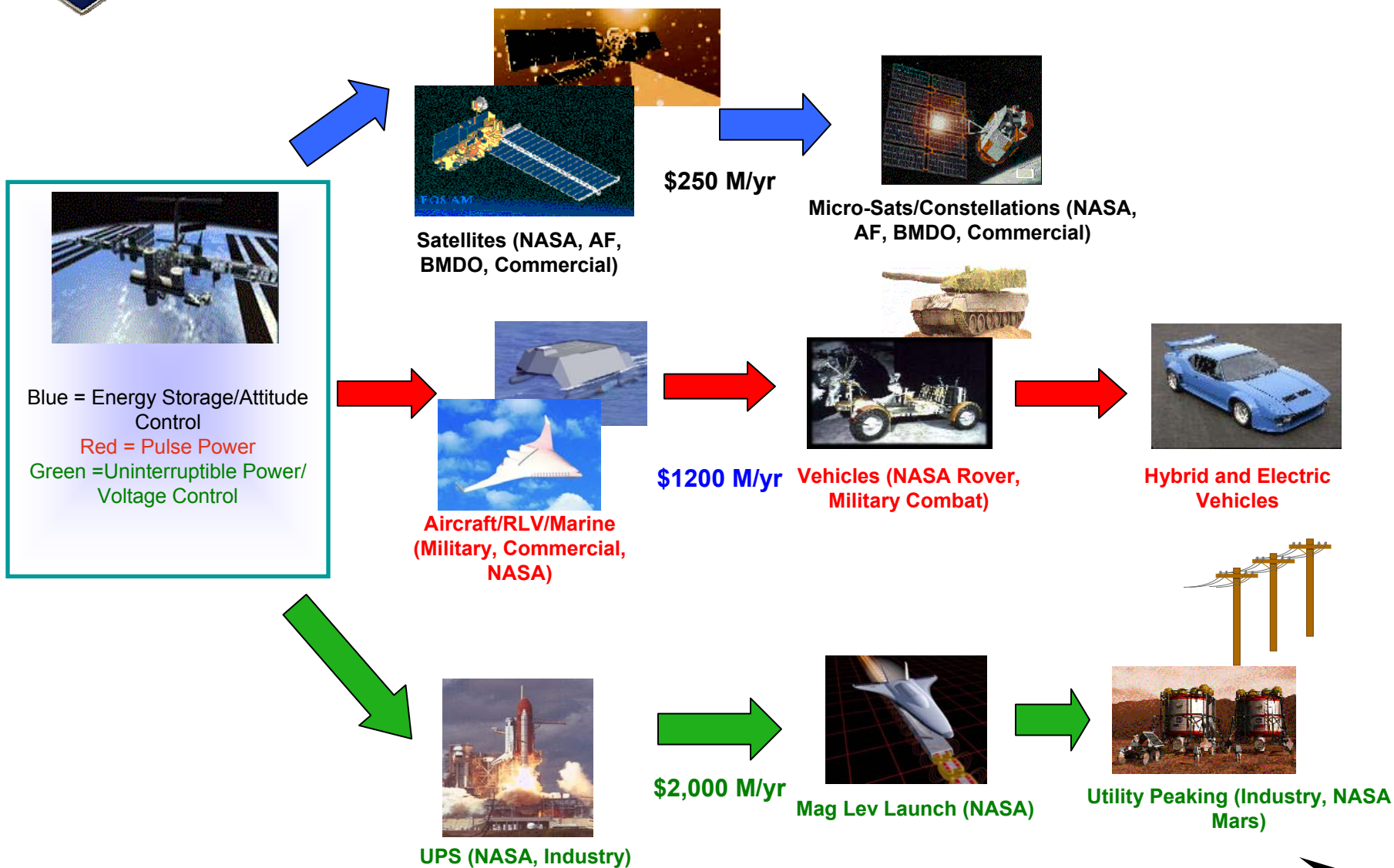
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Potential Flywheel Applications/Markets



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Near Term

WHEN

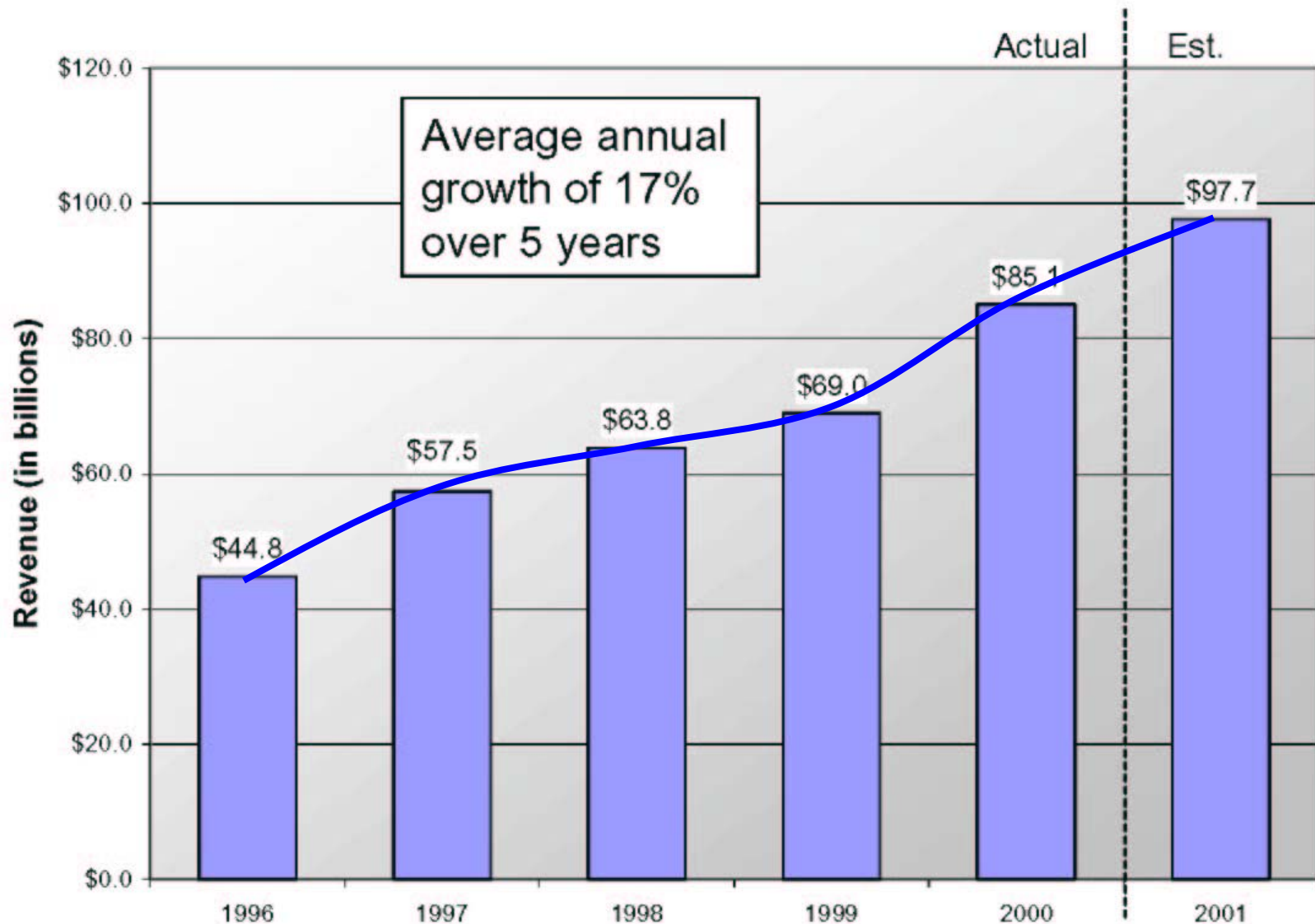
Far Term



Commercial Satellite Industry Growth



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Real World, Dual-Use Examples



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Flywheel Powered Tram

- Peak power
- In service (Bristol)

Beacon Power/Cox Cable

- UPS
- \$XXM Contract



“Incredible Hulk” Roller Coaster

- Peak power/Load leveling
- 0-40 in 2 sec (6000 Amps)
- 4 10,000 lb flywheels





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AF/NASA Technical Approach



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- **Develop advanced aerospace flywheel component and system technologies to meet AF & NASA long term mission needs**
 - **Energy Storage**
 - **Integrated Power and Attitude Control**
 - **Power Peaking & Pulse Power**
- **Near term technology focus on**
 - **“Millenium” class, >1kW-h, for large satellites**
 - **“Century” class flywheels, 300-700 W-h capacity, for mid-sized satellites**
- **Longer term development of flywheels, < 100WHr capacity, for small satellite applications**
- **Demonstrate flywheel technology goals**
 - **System Specific Energy (usable) > 50 W-h/Kg (within 5 years), > 200 WHr/Kg long term**
 - **Conventional Momentum Storage capability at Min. speed (>2x at Max. speed)**
 - **Cycle Life > 75,000**
 - **Round Trip efficiency > 90%**
 - **System Cost Reductions > 25%**



National Aerospace Flywheel Program Players



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DOT/DOE DARPA Army Navy NIST

Other
USAF

USAF
AFRL

NASA
GRC

Other
NASA

AFS-
Trinity

Honeywell

Moog/
USFS

Optimal
Energy
Systems

Flywheel
Vendors

Primes

Boeing

Lockheed-
Martin

TRW

Aerospace
Corp

Applied
Mat'l
Tech., Inc

FESI

Foster
Miller

Mohawk
Innovative
Tech., Inc

Test
Devices

The
Bearing
Consultants

Think
Composites

Toray
America

Other
Businesses

Academia/
Labs

AF
Academy

Air Force
Institute
of Tech

Auburn

Penn St

TX A&M

Univ TX
CEM

Univ
Toledo

Univ VA

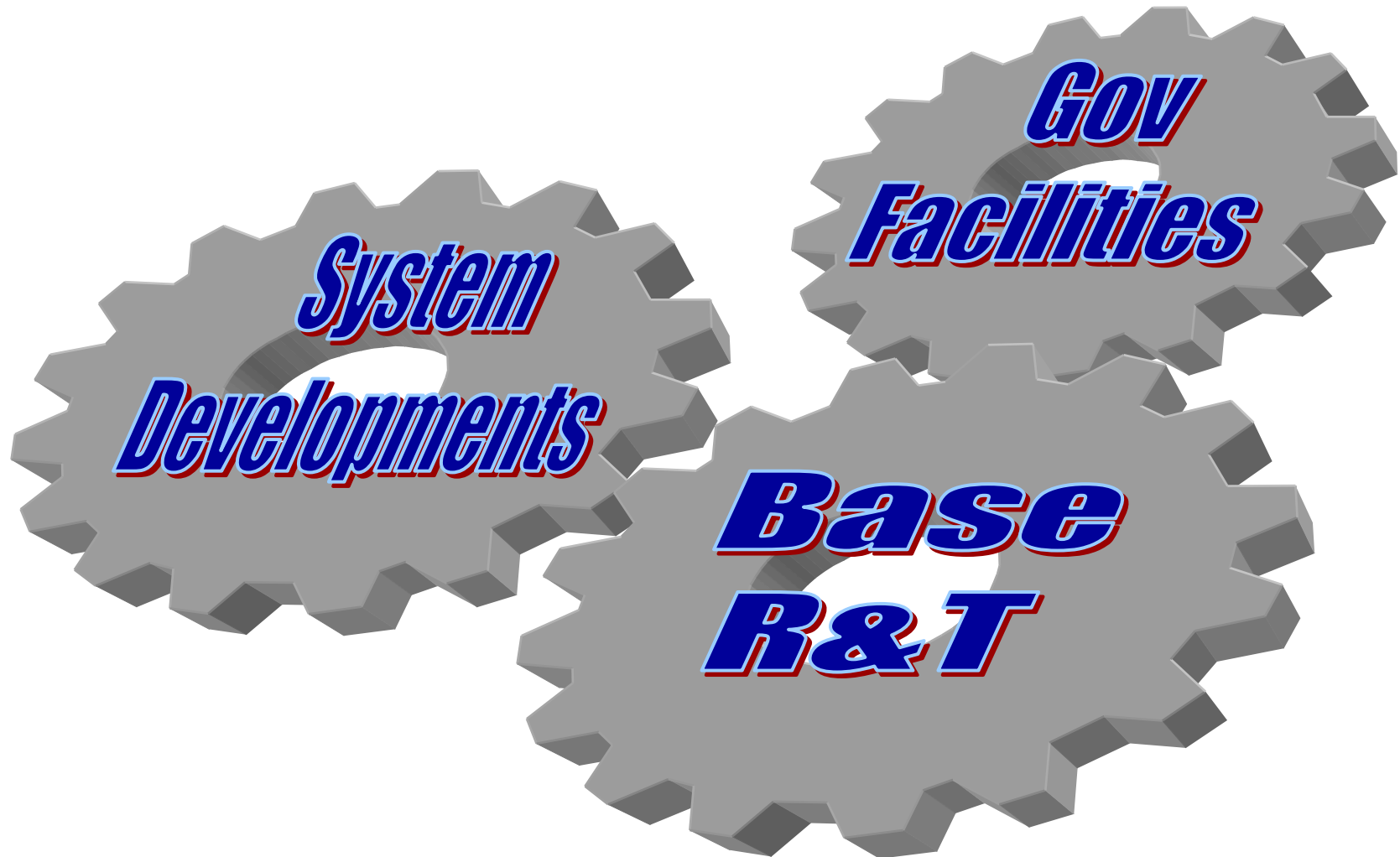
VA Tech



AF/NASA Flywheel Technology Program



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AF System Level Development



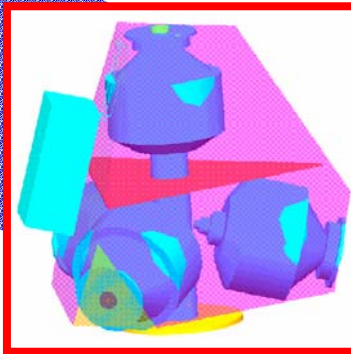
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Integrated Power and Attitude Control System (IPACS) Development

- IPACS testing (Honeywell)
- Flywheel Rotor Safe-Life Program (NASA/Aerospace)
- Magnetic bearing control research (Ga Tech/Va Tech)
- Rotordynamics (Auburn)

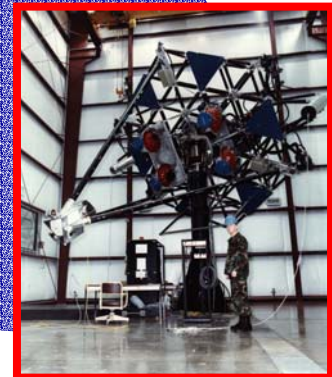
- Simultaneous attitude and charge/discharge control
- Solid modeling of IPACS (Honeywell)
- System level simulation



Flywheel Attitude Control, Energy Transmission & Storage (FACETS) Development

- FEM/Solid modeling of structural test-bed (Boeing SVS/CSA)
- System level mathematical and HWIL simulation (Boeing SVS)
- FACETS HW integration

Agile Multi-Purpose Satellite Simulator (AMPSS) Integrated Demonstration





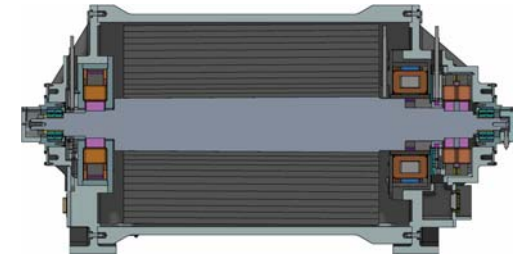
NASA System Level Development



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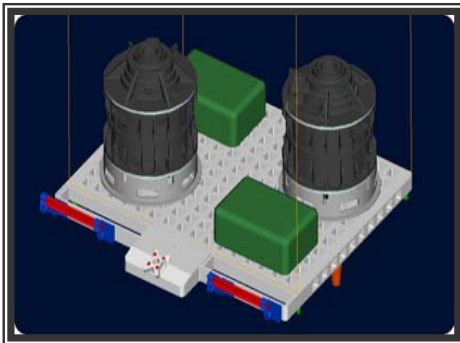
Flywheel Energy Storage Systems (FESS)

- Develop Flywheel Battery Prototype for ISS by 2006
- FESS cancelled at the end of FY01 due to ISS Program budget constraints
- Flywheel Module IDR (Pre-CDR maturity)
Completed in September, 2001 at UT-CEM



Flywheel Express Pallet Experiment, FEPE, Proposed to NASA HQ as Follow-on Effort for FY03 Start

- Build on FESS Hardware Development
- Modules re-sized to 650 WHr each
- Modules counter-rotate and re-circulate power with make-up from ISS
 - Demonstrate technology issues for ISS application





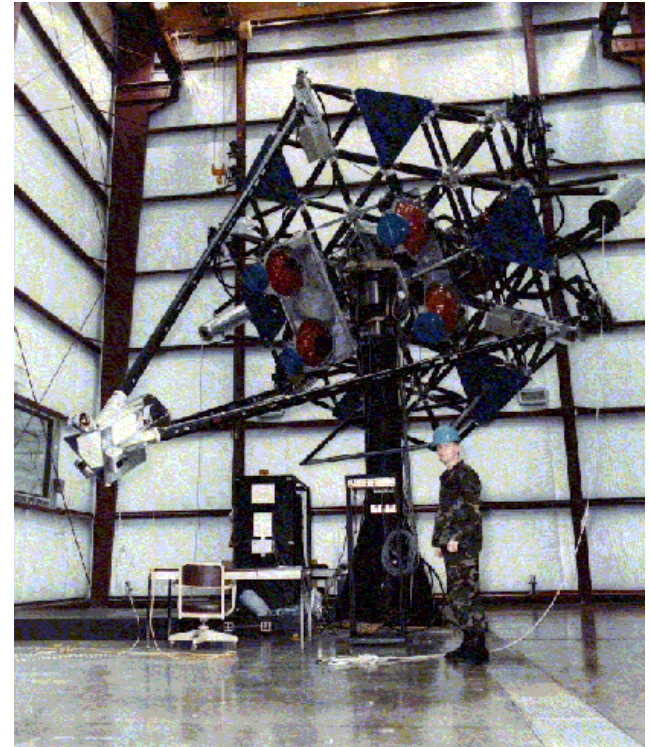
AFRL Agile Multi-Purpose Satellite Simulator (AMPSS)



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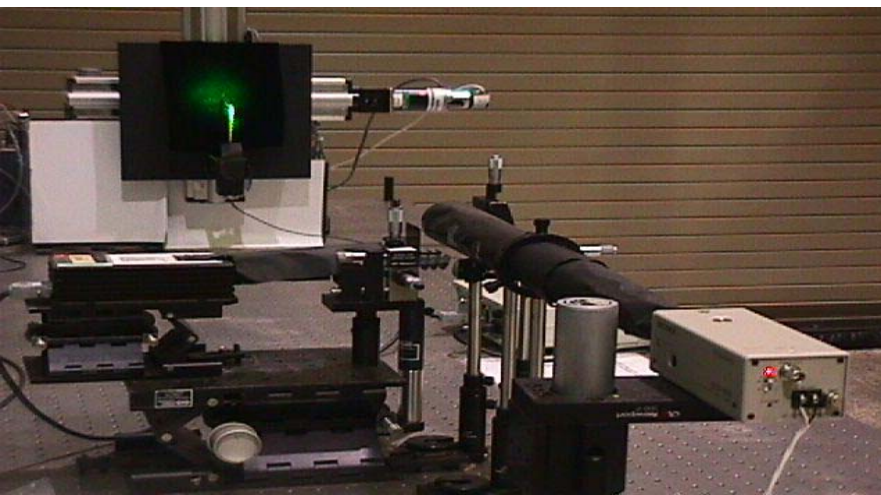
ASTREX

- **Structure:** 1/3 - 1/2 scale beam expander based on SBL concept (graphite/epoxy)
- **Spherical Air Bearing**
 - Load capacity: 14,500 lb (air pressure dependent)
 - $\pm 20^\circ$ Pitch and Roll, $\pm 180^\circ$ Yaw
- **“Smart Structure”** with embedded piezo-ceramic sensors/actuators for structural vibration control



Optical ATP

- **Optics:** Table-top demonstration
- To be tested in coordination with attitude control (flywheels / cmgs) on ASTREX for ATP function





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NASA Flywheel Testbed



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- **Objective**
Enable system level demonstrations of advanced technologies
- **Test Capabilities**
 - Low Energy Flywheel Facility (LEFF) - single units, < 350 whr
 - High Energy Flywheel Facility (HEFF) —multiple units on air table, < 700 whr, < 540 Kgs
- **Status**
 - LEFF Operational
 - HEFF 90% Complete, Operational in 2002
 - Conduct two-unit torque and power testing on mag bearings in HEFF thru 2003



Control Room



LEFF



HEFF



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Base R&T - Rotor



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Multi-directional Composite Rotor Development

(Auburn Univ., CCDS Cooperative Agreement – NASA)

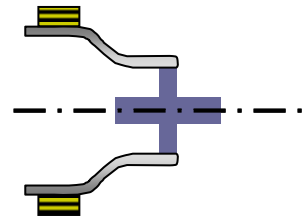


Optimal Rotor Design/Manufacturing

Optimal distribution of material properties
(Think Composites, SBIR/in-house – AFRL)

Integrated Composite Arbor and Flywheel Rim Technology Development

Development, proof and cyclic tests of high tip speed rotors
(Univ. of Texas, Center for Electromechanics, NRA – NASA)



Characterization & Control of Internal Material Damping in Composite Rotors

(Auburn Univ., NRC Summer Faculty Fellowship – AFRL)

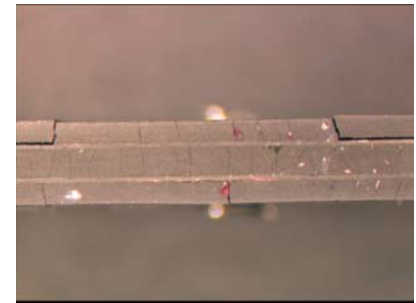


Flywheel Rotor Safety/Longevity Program



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- **Flywheel Rotor Safety/Longevity Working Group**
 - Co-Sponsored by NASA and AFRL and chaired by Aerospace Corporation, Mr. Jim Chang
 - Three Working Group meeting have been held (June and December 2001 and March 2002)
 - Draft of Rotor Certification Standard in review
- **Material Characterization and Life Prediction**
 - Preliminary results reported at ASTM Symposium
 - Task on hold until FY03
- **Rotor Cyclic Fatigue Testing**
 - FESS Control Rotor testing initiated in FY01
 - Facility failures have slowed progress
 - Facility repairs complete and operational checkouts are in progress
 - Testing of UT-CEM PLM rotor and FESS control rotor to be completed in FY02
 - Cycling of FESI IPACS rotor continues

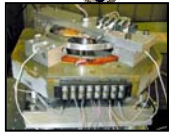




Base R&T - Bearings



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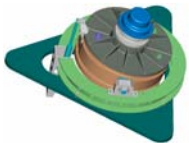
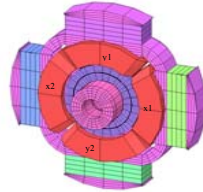


Low/Zero Bias Magnetic Bearing Control

Applied Advanced Nonlinear Control (Georgia Tech, AFOSR – AFRL)

Low-loss, fail-safe magnetic suspension for flywheels

Fault-tolerant bearings; hybrid controls; bearing design tool; expert system for health monitoring (Texas A&M, CCDS Cooperative Agreement – NASA)



Magnetic Bearing Control in the Presence of Base Motion (VirginiaTech, AFOSR – AFRL)

Advanced Flywheel Materials Development for High Specific Energy

Develop high-strength materials for flywheel magnetics (UT-CEM, NRA – NASA)

Stator-controlled Magnetic Bearing Development

Revolutionary Magnetic Bearing Concept (MITI, Phase II SBIR – AFRL)

Flywheel Energy Storage Systems for Small and Medium Spacecraft

Develop high-speed passive radial bearing system (Foster-Miller, Phase II SBIR – NASA)

Novel Damping Concepts for Mechanical Backup Bearings and Passive Magnetically Suspended Rotors (Univ. of Toledo, NRA – NASA)

Computational Tracking of Dynamic States / Disturbances in Rotating Machinery *Observer-based magnetic bearing control using extended Kalman filter approach* (NASA)²⁵



Base R&T - System



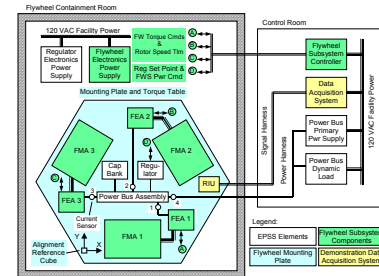
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Coordinate Momentum and Energy Transfer (COMET™)

3-DOF System Demonstration in NASA HEFF
(LMCO-CPC, NRA – NASA)

Simultaneous Energy Storage & Attitude Control

Collaborative control algorithm development
(Air Force Academy, Ga Tech EPA – AFRL)



Flywheel Technology Development for Small Satellites

Develop high-speed motor & drive for open core flywheel system
(Penn State, NRA – NASA)

New Concepts in Low Cost, Higher Reliability and Less Complex Flywheel Systems

Basic research in passive bearings and inside-out flywheel configurations
(NASA)



Outline



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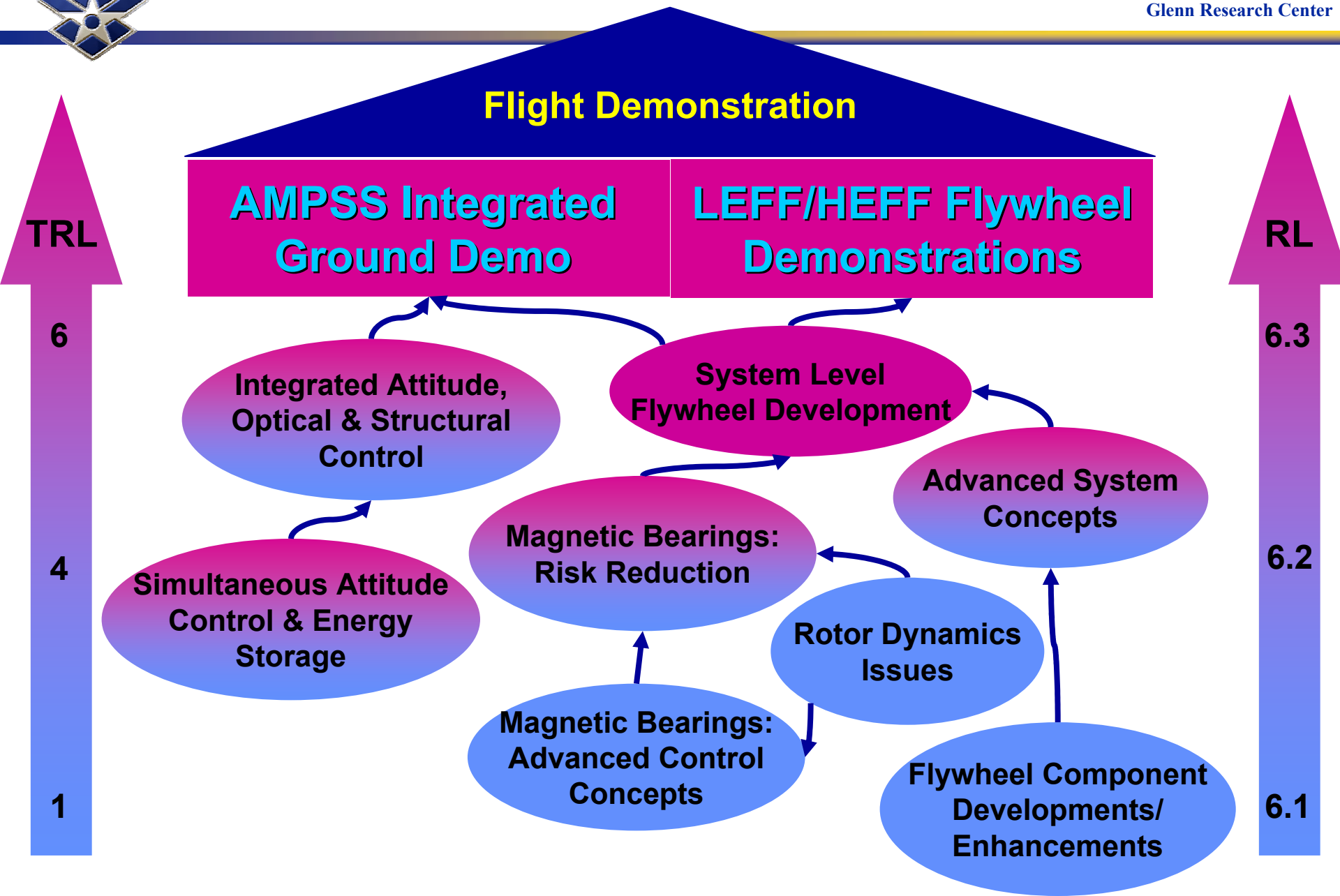
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Summary



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Conclusions



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- **AF/NASA Aerospace Flywheel Program has faced significant challenges (and some triumphs)**
- **Now more robust than ever**
 - Focus on risk reduction and potential users
 - Highly leveraged
 - Multi-disciplinary (govt/industry/academia) cooperative effort
- **Future is bright**
 - Pushing forward with system level demonstration (AMPSS, LEFF, HEFF)
 - Maintaining critical base R&T efforts
- **We will make it happen – FLIGHT DEMONSTRATION**